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APPENDIX B-2

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# INTRODUCTION TO D-$^3$He FUSION REACTORS

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## I. INTRODUCTION

Research on producing controlled thermonuclear fusion reactors, with the goal of developing commercial central-station power plants, has been pursued around the world since the late 1950's. Most of the effort during these four decades has been devoted to harnessing the deuterium-tritium fusion reaction,

$$ {}_1^2D + {}_1^3T \rightarrow {}_2^4He + {}_0^1n, $$

in which the $\alpha$ particle (${}_2^4He$) has an energy of 3.5 MeV and the neutron has an energy of 14.1 MeV. This reaction has been emphasized because it has the largest cross-section under laboratory conditions, and because both D and T (bred from Li) are readily available.

Another fusion reaction, namely

$$ {}_1^2D + {}_2^3He \rightarrow {}_2^4He + {}_1^1p \rightarrow 18.4 \text{ MeV} $$

has long been recognized as offering certain significant advantages over the D-T reaction, which arise mainly from the fact that no neutrons are produced. Nevertheless, D$^3$-He plasmas have not been experimentally investigated to any great degree due to the scarcity of terrestrial $^3$He. The recent discovery of significant amounts of $^3$He in the lunar regolith, however, has prompted a critical re-examination of the advantages and disadvantages, relative to "conventional" D-T fusion, which would accrue from the use of the D-$^3$He cycle. This work was initiated and has been pioneered by the Fusion Technology group at the University of Wisconsin, which was the first to recognize the importance of the lunar $^3$He resource

for terrestrial fusion.[1] Other groups, including the Lawrence Livermore Laboratory, the University of Illinois, Spectra Technology, Inc. and the Institute of Plasma Physics at Nagoya University, have begun studies in this area. The purpose of this appendix is to summarize the findings of these studies. An earlier account of the work can be found in the Proceedings of the Lunar $^{3}$He Fusion Power Workshop[2] in which the fusion power working group concluded: "There appear to be significant potential advantages to a D-$^{3}$He fueled fusion reactor. These advantages could become compelling with respect to environmental[A safety, licensing, and public acceptability."

## II. FUSION REACTORS

A simplified schematic cross-section of a conventional D-T based magnetic fusion reactor is shown in Fig. 1. The plasma or fusion fuel, which consists of electrically-charged particles, is confined in a vacuum chamber, away from the walls, by magnetic fields created by superconducting magnets. The plasma core is surrounded by a "first wall" which absorbs most of the radiant heat load and some of the plasma particle energy, a blanket which absorbs the neutron energy and breeds tritium, a shield to protect the magnets and prevent all radiation leakage to the outside, and finally, by the magnets. The heat produced in the first wall structure and blanket is used to power a thermal cycle and generate electricity by conventional means.

In addition to the "toroidal" confinement device typified by the Tokamak shown in Fig. 1, there exists a class of cylindrical or simply connected confinement configurations, including tandem mirrors, FRC's and spheromaks, which have certain potential advantages and disadvantages relative to Tokamaks; these are discussed briefly later in this report.

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1. L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, Fusion Techn. 10 167 (1986).

2. Proceedings of the Lunar $^{3}$He Fusion Power Workshop, April, 1988, Cleveland.

Fusion plasma physics research has been directed at achieving a level of understanding of plasma confinement and heating which would lead to the attainment of parameters necessary to create a sustained, controlled fusion reaction. The intermediate goal is to demonstrate this in devices of the appropriate scale to ultimately be developable into commerically-competitive power plants. Most of the effort has been concentrated on Tokamaks, which have achieved the required temperatures, and are within a factor of three of the required "confinement parameter" $n_i \tau_e \sim 2 \times 10^{20}$ ions-seconds/$m^3$, where $n_i$ is the ion density and $\tau_e$ the energy confinement time. The other magnetic fusion confinement concepts mentioned above have received far less study and are not as advanced, although progress is very rapid with some of them.

In the past two decades, fusion research has expanded beyond plasma physics to include a major effort in technology, including reactor system studies and component development. Key materials problems have been identified, which arise principally from the energetic (14.1 MeV neutrons) produced in the D-T reaction. These lead to degradation of material properties, particularly at high temperatures, which will probably necessitate replacing the first wall and inner blanket of a D-T based reactor every three to five years. In addition, induced radioactivity associated with these energetic neutrons leads to moderate afterheat and waste disposal problems, although they are significantly less severe than for fission systems.[3]

## III. GENERIC ADVANTAGES AND DISADVANTAGES OF THE D-$^3$He FUSION CYCLE

A summary chart of the relative merits of D-T and D-$^3$He cycles is shown in Table 1. As mentioned in the introduction, the principal reaction, D + $^3$He $\rightarrow$ $^4$He + p, produces no neutrons. All of the energy is produced in the form of charged particles. Some of the energetic charged particles escape from the confined plasma volume fairly quickly and can be used for direct energy conversion, leading to higher efficiency and reduced waste heat. The

3. "The ESECOM Committee Executive Summary," J. Holdren et. al., Fusion Techn. 13 7 (Jan. 1989).

balance of the energy released serves to heat the plasma; in steady state this heating is balanced by radiation, convection, and conduction losses. The relative magnitudes of these loss mechanisms depends on the confinement scheme.

Although the primary D-$^3$He reaction produces no neutrons, a few are produced from side reactions involving D-D and D-T fusions. The fraction of total energy produced in neutrons, however, is typically four percent at $T_e$ = 50 keV for a 50:50 D-$^3$He mixture, and can be made much lower (<1%) by reducing the D concentration or increasing $T_e$, at some cost in fusion power density. When this is compared with the 80% fraction of fusion energy in neutrons for a pure D-T cycle, the enormous technological advantage of D-$^3$He becomes apparent.

The relative absence of neutrons has several advantages. First, the radiation damage is drastically reduced, and reactors can be designed whose components should survive the entire lifetime of the reactor[4] based upon state-of-the-art materials. This should result in decreased maintenance and increased capacity factor, which favorably impacts the economics. Secondly, the reduced activation makes possible passively safe reactor designs, which should greatly speed the licensing process and further reduce costs. Third, the low level of induced radioactivity simplifies the decommissioning of the end of plant life.

In the D-$^3$He cycle, a large fraction of the reaction energy appears in the form of charged particles and synchrotron radiation. In principle, each of these can be converted directly to d.c. electricity without the necessity of going through a thermal cycle. Thus, the efficiency can be very high; estimates of 60-70% appear to be realistic. This reduces the waste heat significantly, and results in smaller plant sizes for a given electric power output. Avoidance of the thermal cycle would also permit operation of the first wall and structural material at low temperature, where radiation damage is reduced.

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4. G. Kulcinski et. al., "Apollo - An Advanced Fuel Fusion Reactor for the 21st Century," University of Wisconsin Report UWFDM-780 (Oct. 1988).

The principal disadvantage of the D-$^3$He cycle is generally believed to result from its relatively low fusion power density. Because the fusion reaction cross section is smaller and the required temperatures are higher, the fusion power production rate per unit volume is about two orders of magnitude lower id D-$^3$He than in D-T, at a given magnetic field strength and value of $\beta$, where $\beta$ is the ratio of plasma pressure to magnetic pressure. The fusion power density varies as $\beta^2B^4$. In low $\beta$ devices such as Tokamaks ($\beta \lesssim 10\%$) this results in somewhat larger required plasma volumes and higher fields, for ignition in D-$^3$He than in D-T mixtures. In high $\beta$ devices such as FRC's, however, where $\beta$ = 60-90%, the fusion power density can be kept very high even with moderate magnetic fields, so that other factors determine the reactor size. These tradeoffs are illustrated in examples given in the following sections.

We now turn from the generic advantages of the D-$^3$He fusion cycle to a brief discussion of the relative advantages of two confinement approaches, the Tokamak and the FRC.

## IV. D-$^3$He TOKAMAKS

The Tokamak represents the conventional, most developed low-$\beta$ approach to magnetic fusion. There have been two fairly detailed studies of D-$^3$He based Tokamaks, the Apollo design (4) from the University of Wisconsin, and "case 8" of the ESECOM (3) study, which compared fission, D-T fusion, and D-$^3$He fusion. We use the former to illustrate general features. The most important parameters are listed in Table II. Tokamaks are toroidal magnetic traps, and have achieved higher temperatures and confinement parameters than any other approach. Scaling laws tend to make them fairly large, typically > 2500 MW (thermal). Due to their low $\beta$ values, dictated by stability considerations, they operate at relatively high magnetic field strengths, particularly when D-$^3$He is the fuel cycle.

Because of the high magnetic field permeating the plasma, a large fraction of the energy loss is in the form of synchrotron radiation, which is narrow band and can in principle by converted directly to electricity at high

efficiency by using rectifying antennas ("rectennas"). Rectennas which would operate at the required frequencies are currently under development. Thus, the D-$^3$He Tokamak should be able to operate at relatively high plant efficiencies, and it may even be possible to dispense entirely with the usual thermal conversion cycle. Such an approach has been adopted for some of the Apollo cases. Typical parameters for an Apollo design are shown in Table II. It is not considerably larger than competing D-T tokamaks, due to the use of high field magnets, and space savings accomplished by reduced radiation shielding requirements. The plasma current, while large, is driven primarily by synchrotron radiation and the "bootstrap" effect, and requires only modest external current drive. Of particular interest and importance is the very low neutron wall loading, of 0.1 MW/m$^2$, allowing for a 1st wall which does not need to be replaced during the reactor lifetime.

## V. D-$^3$He FRC's

The FRC is a linear device with closed poloidal field lines and no toroidal field, as shown schematically in Fig. 2. As a result its $\beta$ value is between 70% and 90%, providing very high fusion power densities at modest field strengths of typically 4-9 Tesla, well below state-of-the-art. FRC physics is less advanced than that of Tokamaks. However, experimental FRC research in the last decade has produced energetic, stable plasmas with very good confinement parameters. Larger, proof-of-principle experiments are presently under construction.

The only studies carried out for FRC reactors were simple conceptual designs done 5-9 years ago,[5 6 7] so that it is not possible to make detailed quantitative cost estimates such as have been done for D-$^3$He Tokamaks. However, the higher fusion power density of FRC's would be expected to result in slightly lower cost of electricity than for Tokamaks,

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5.G. Miley et. al., The SAFFIRE Reactor Concept, EPRI Report AP-1437, (1980)

6.R.L Hagenson and R.A. Krakowski, The CTOR Reactor, Los Alamos Report LA-8758-MS (1981)

7.G.C. Vlases et. al., Fusion Technology 9 116 (1986)

based on generally accepted principles of fusion reactor design. Although no detailed FRC designs exist, simple plasma physics models of a D-$^3$He reactor can be used to illustrate important features of an FRC reactor. These are shown in Table II and illustrate the substantial differences between Tokamak and FRC designs.

Two cases are shown. The first is very field (4T) design and achieves power densities and first wall fluences similar to those of Apollo in a slightly smaller volume. The second design is a very compact, high power density system in which the unit size can be quite small. Although the wall neutron load here is higher, it is still an order of magnitude lower than for a D-T Tokamak, and thus first wall replacement would occur only once every 10-15 years.

Synchrotron losses in an FRC are quite low due to the high $\beta$, so that power extraction schemes would probably concentrate on direct conversion of the charged particle energy. If a thermal cycle is used, the particle heat load on the wall can be reduced as much as desired by using the natural divertor geometry to advantage. The D-$^3$He FRC looks to be particularly attractive for space power and propulsion applications by virtue of its very high power density, reduced shielding requirements, and reduced radiator mass.

## VI. CONCLUSIONS

Both Tokamaks and FRC's offer certain advantages, and the ultimate decision as to which to pursue for terrestrial power generation will depend heavily on how the physics performance of each of them develops over the next few years. Whether the final choice is for Tokamaks, FRC's, or other confinement approaches such as Stellarators, Reversed Field Pinches, or Mirrors, it is clear that the D-$^3$He fuel cycle offers clear advantages over the D-T cycle. Although the physics requirements for D-$^3$He are more demanding, the overwhelming advantages resulting from the two order of magnitude reduction of neutron flux is expected by many fusion reactor designers to lead to a shorter time to commercialization than for the D-T cycle.

Table 1

| | D-T Cycle | D-$^3$He Cycle |
|---|---|---|
| Advantages | High Fusion Power Density<br>Easier Ignition<br>Readily Available (Terrestrial) Fuel Supply | Very Low Neutron Fluence, Which Implies:<br>o Reactor Lifetime 1st Wall<br>o Low Activation<br>o Easier Licensing<br>High Fraction of Directly Convertible Reaction Energy |
| Disadvantages | Difficult Materials Problems<br>Frequent 1st Wall Changeout<br>Some Afterheat Problem<br>Requires Thermal Cycle<br>More Difficult De-Commissioning | Lower Fusion Power Density<br>No Terrestrial $^3$He |

## SCHEMATIC OF TOKAMAK REACTOR CORE

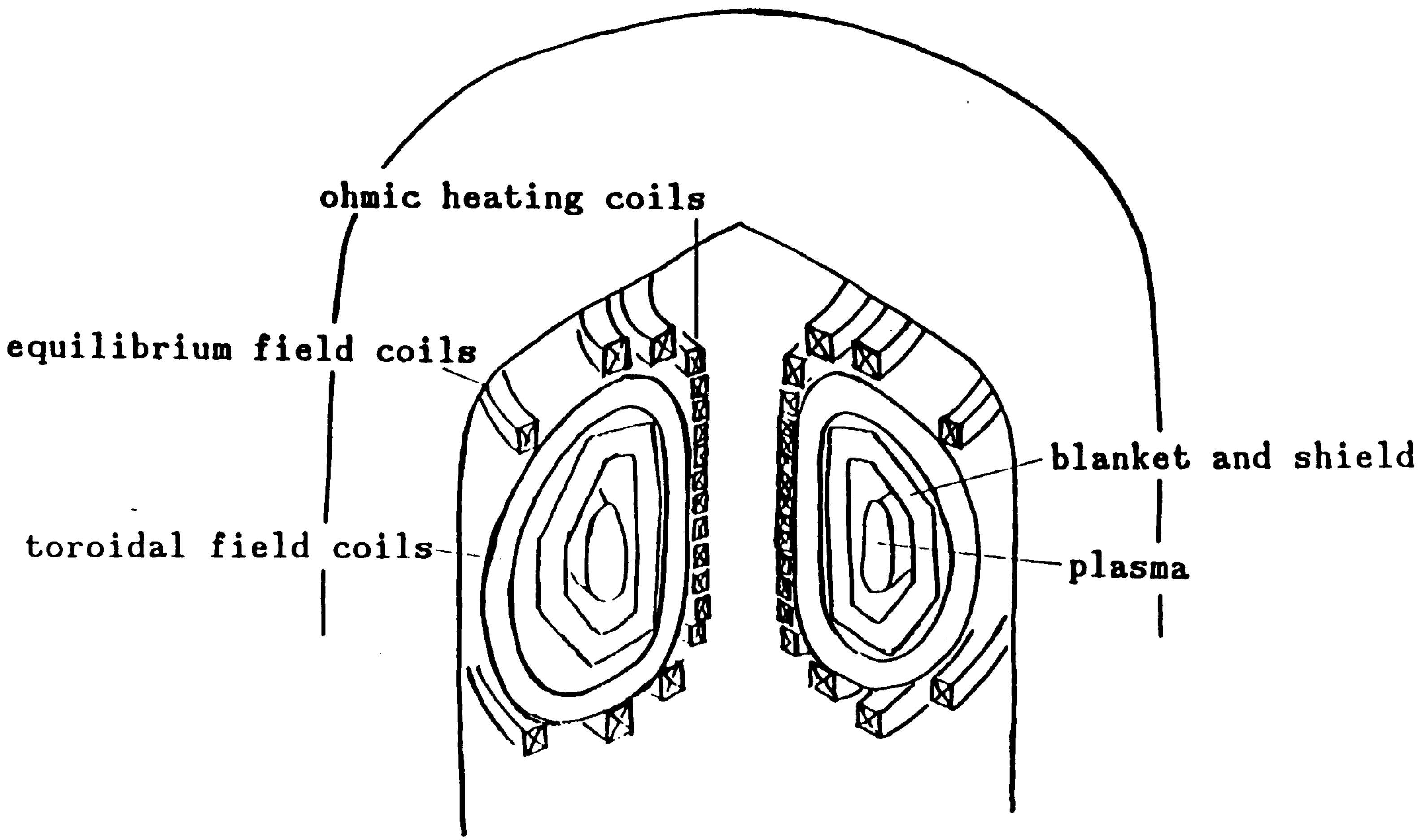


Figure 1

# SCHEMATIC OF FRC REACTOR CORE

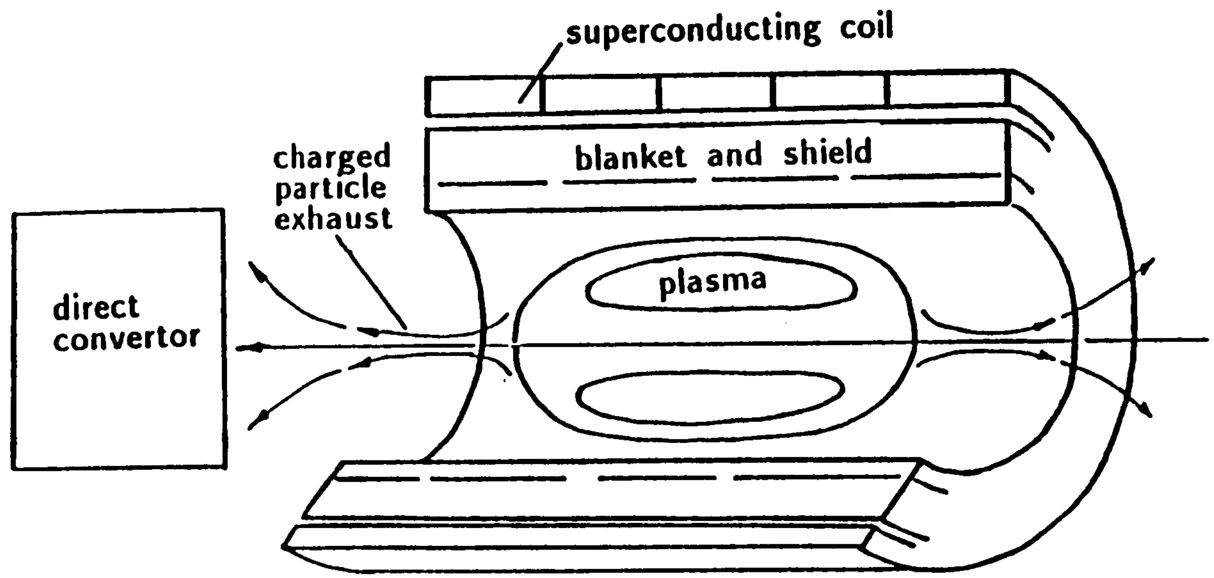


Figure 2

## COMPARISON OF D-$^3$He TOKAMAK AND FRC REACTOR PARAMETERS: POWER FLOW CHARACTERISTICS

| | TOKAMAK (APOLLO DESIGN) | FRC LOW-B | FRC HIGH-POWER DENSITY |
|---|---|---|---|
| **Overall Power Production** | | | |
| Fusion Power (MW) | 2872 | 3072 | 254 |
| Electric Power (MW) | 1200 | 1200 | 100 |
| **Breakdown of Power Types (MW)** | | | |
| Charged Particles | 287 | 1524 | 119 |
| Neutrons | 118 | 66 | 6 |
| Synchrotron Radiation | 1626 | 258 | 29 |
| Bremsstrahlung Radiation | 959 | 1224 | 101 |
| **Wall Loadings** | | | |
| Neutron Loading ($MW/m^2$) | 0.10 | 0.12 | 0.21 |
| Radiant Loading ($W/cm^2$) | 91 | 250 | 500 |
| Fusion Power Density ($MW/m^3$) | 2.03 | 4.6 | 30 |

Table II, part 1

## COMPARISON OF D-$^3$He TOKAMAK & FRC REACTOR PARAMETERS: PLASMA & FACILITY SIZE PARAMETERS

| | TOKAMAK (APOLLO DESIGN) | FRC LOW-B | FRC HIGH POWER DENSITY |
|---|---|---|---|
| **Magnetic Fields** | | | |
| at coil (T) | 20 | 5 | 8 |
| at plasma (T) | 12.9 | 5 | 8 |
| **Plasma Size and Shape** | | | |
| Major Radius (m) | 8 | 1.9 | 0.54 |
| Minor Radius (m) | 2.0 | 0.8 | 0.22 |
| Volume ($m^3$) | 1410 | 670 | 8.4 |
| Aspect Ratio | 4 | (1) | (1) |
| Elongation | 2 | 5.4 | 3 |
| **Plasma Parameters** | | | |
| Ion Temperature (keV) | 69 | 80 | 80 |
| Ion Density ($10^{20} m^{-3}$) | 1.3 | 2.3 | 5.8 |
| Average Beta | 0.06 | 0.9 | 0.9 |
| $n\tau_E$ ($10^{20} m^{-3} s$) | 48 | 17 | 18 |

Table II, part 2